Surface Gravity Waves And Coupled Marine Boundary Layers

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Award #: N00014-00-C-0180
http://www.onr.navy.mil/sci_tech/ocean/Info/dri00/CBLAST00.htm

LONG-TERM GOALS

The long term objective of our research is to advance the understanding of air-sea interaction and the coupling between the atmospheric and oceanic boundary layers (the ABL and OBL) mediated by the surface gravity wave field, in order ultimately to develop better parameterizations of the boundary layers and surface fluxes for coupled, large-scale numerical models. Turbulence-resolving, large-eddy and direct numerical simulations (LES and DNS) are the main tools to be used to investigate interactions among the ABL, OBL, and the air-sea interface. Using numerically generated databases, we intend to investigate: (1) vertical heat and momentum fluxes carried by wave-correlated winds and currents; (2) enhanced small-scale, turbulent energy, mixing, and dissipation due both to enhanced wave-correlated wind and current shears and to wave breaking; and (3) wave-averaged influences due to mean Lagrangian currents (Stokes drift) that give rise to coherent Langmuir circulations in the ocean. These mechanisms will be considered for a variety of surface wave states. Finally, we intend to make an effort to connect our simulation results with the proposed Coupled Boundary Layers Air-Sea Transfer (CBLAST) field campaigns.

OBJECTIVES

Our recent research efforts have focused on the interaction between an imposed surface gravity wave and stratified turbulence in the ABL. Of particular importance is the dependence of the form stress (drag) on stratification over a range of wave age c/u_*, where c is the wave phase speed and u_* is the friction velocity.

APPROACH

We are investigating interactions among the ABL, OBL, and the connecting air-sea interface using both LES and DNS. The premise behind this approach is that the fundamental processes that lead to air-sea coupling will manifest themselves in three-dimensional, time-dependent simulations. Hence, the creation of sufficient numerical databases will allow for the interpretation of air-sea

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**
4. TITLE AND SUBTITLE **Surface Gravity Waves And Coupled Marine Boundary Layers**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Center for Atmospheric Research,,Boulder,CO,80307**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

interaction. The LES code adopted for our work evolves from the efforts of Moeng (1984), Sullivan *et al.*(1994), Sullivan *et al.*(1996), and McWilliams *et al.*(1997). The spatial discretization in our LES is pseudospectral in horizontal directions and finite difference in the vertical, with third order Runge-Kutta time stepping. A novel nesting procedure allows for fine nested meshes to be embedded within an outer coarse grid. A recently developed DNS code that accommodates a temporally and spatially varying lower boundary (Sullivan *et al.*2000) is also being extensively used. DNS has served a dual role in our research; it provides a clean framework for testing LES developments and the DNS results have provided insight into flow over moving surface gravity waves.

WORK COMPLETED

Several tasks relevant to the current project were completed and or initiated during the past fiscal year. To date we have concentrated our effort on examining the coupling mechanisms among surface gravity wave fields and stratified atmospheric turbulence, developing a framework for posing LES of the ABL and OBL with wave effects, enhancing a large scale ocean parameterization, and developing efficient computer codes. Highlights from the first three efforts are described further in the next section.

The development of efficient computer codes is one of the technical aspects that must be addressed in order for our research to be successful. In anticipation of the large numbers of gridpoints required for our simulations, we undertook a code conversion project to move our existing “flat” LES code (*i.e.,* the LES code with no surface geometry) from a shared memory (Cray vector supercomputer) environment to a distributed memory massively parallel (*e.g.,* IBM SP3 supercomputer) environment. We have rewritten our simulation codes to use both the Message Passing Interface (MPI) and OpenMP programming libraries. Initial tests of the new codes indicate that they scale well, *i.e.,* the wall clock time decreases linearly as the number of MPI processes increases. To date, we have efficiently used as many as 100 processes on the IBM SP3 for problems with 25×10^6 gridpoints.

RESULTS

In the past year, we published an archival manuscript (Sullivan *et al.*2000) and two meeting papers (Sullivan *et al.*1999; Sullivan & McWilliams 2000) describing the technical developments and analysis of DNS of stratified turbulent flow over a series of moving waves as depicted in Figure 1. The flow considered is a three-dimensional, turbulent, Couette flow over a series of heated (or cooled) two-dimensional, monochromatic, deep-water gravity waves with orbital velocities given by first-order wave theory. The external forcing of the flow occurs through a constant velocity U_o and a thermal gradient $\triangle\theta = \theta_L - \theta_u$. Both unstable $\theta_L > \theta_u$ (hot waves) and stable $\theta_L < \theta_u$ (cold waves) stratification are considered. Despite the relative simplicity of this model flow, the presence of a moving wavy lower boundary is sufficiently complicating that a new numerical method had to be developed to simulate turbulent flow in this geometry. The new algorithm is a mixed pseudospectral finite-difference scheme that utilizes a surface fitted grid, a conformal mapping between physical and computational space, and a co-located grid architecture for all variables.
Our new DNS code was used to model stratified turbulent flow over a monochromatic water wave with varying waveslope ak and wave age c/u_* at a bulk Reynolds number $Re = U_o h/\nu = 8000$ with Rayleigh number $Ra = g\beta\triangle\theta h^3/\nu\alpha = [6, 2, 0, -2]10^6$, and Prandtl number $Pr = \nu/\alpha = 1$. In this initial investigation, DNS as opposed to LES was used because of the absence of a complicating SGS model that includes wave effects and the simplicity of the surface boundary conditions. Results from these DNSs show that the level of stratification influences the flowfields above moving water waves. The magnitude of the surface form stress can vary by as much as a factor of 3 depending on the level of stratification and the wave age. We found a good collapse of the surface drag

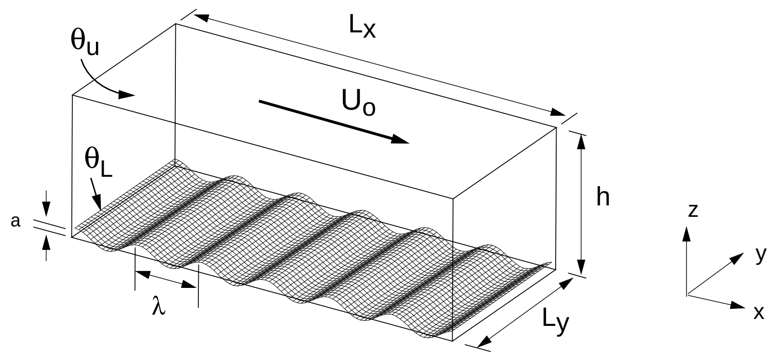

Figure 1: **Sketch of 3D stratified Couette flow driven by velocity U_o over a moving wavy boundary of wavelength λ (wavenumber $k = 2\pi/\lambda$), phase speed c, amplitude a, and waveslope $ak = a2\pi/\lambda$ in a domain of size $(L_x, L_y, h) = (6, 5, 1)\lambda$ (see Sullivan *et al.*2000). The Boussinesq fluid has temperature, density, viscosity, and thermal conductivity $(\theta, \rho, \nu, \alpha)$, respectively. Surface temperatures of the wave and upper boundary are θ_L and θ_u, and the friction velocity u_* is based on the constant stress $\tau = \rho u_*^2$. Here the coefficient of thermal expansion $\beta = 1/\theta_o$ where θ_o is a reference temperature.**

variation, over a wide range of stratification (unstable, neutral, stable), using the friction velocity u_* to normalize the drag and wave age (see figure 3). A good correlation between the position of the critical layer (see Figure 2) and the drag level was observed; as $z_{cr} \downarrow D_p \uparrow$.
In McWilliams & Sullivan (2000a) an overview of the effect of surface waves on winds and currents in marine boundary layers is presented. This work also develops a framework for posing ABL and OBL LES problems with wavy boundaries which will be evaluated as part of our future research. In the ABL, two workable avenues can be considered: an equilibrium situation where the input to LES is the empirically determined relationship between C_D and wind speed U_{10} for various wave ages, or the alternative is to modify the conventional LES drag law for wave effects. The former approach has the advantage that direct measurements of the total surface drag enter into LES, but the method is not easily generalized to include wind-wave disequilibrium, stratification, and other effects since the available measurement database does not span a broad range of flow conditions. The second approach is the method most often used in second-order closure modeling in flow over stationary hills and uses a “drag-law” imposed at the wavy surface for the unresolved surface roughness. In the OBL, the coupling between waves and turbulent motions is stronger than in the atmosphere because of wave breaking and the formation of Langmuir circulations. Plunging breakers are carried into the interior of the OBL and their inertia also disturbs the near-surface currents over a much larger distance. An option for OBL LES is then to use the Craik-Leibovich wave-averaged dynamical equations but with a modified SGS turbulent kinetic energy (TKE) model to incorporate non-conservative wave-breaking influences.

An important goal of CBLAST research is to distill from the large body of physical evidence relatively simple parameterization schemes that can then be used in large scale models. In a recent work, McWilliams & Sullivan (2000b) analyzed LES cases with surface-wave-averaged dynamical equations. These results show that the effect of Langmuir circulations is to make the vertical mixing substantially more efficient for both material properties and momentum. We also provide a new confirmation that our previously proposed K-Profile Parameterization (KPP) model (Large *et al.*1995) accurately characterizes the turbulent transport in a weakly convective, wind-driven

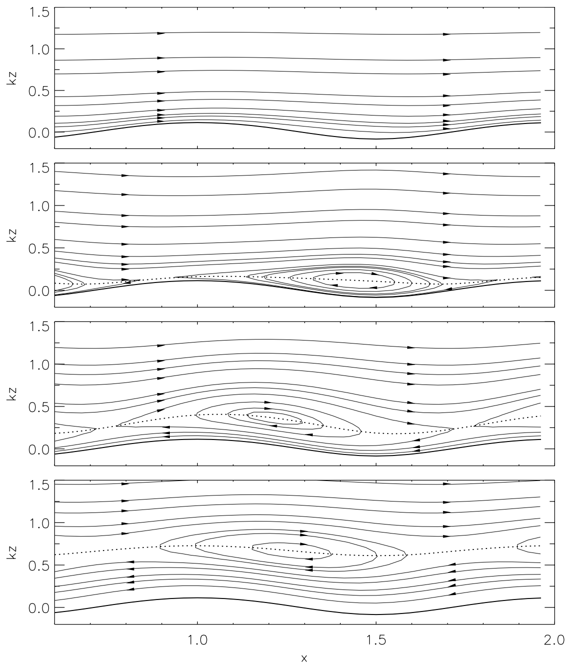

Figure 2: **Phase averaged streamlines over stationary and moving waves with $ak = 0.1$, $Ra = 0$ in surface fitted coordinates: upper, $c/u_* = 0$; upper middle, $c/u_* = 3.9$; lower middle, $c/u_* = 7.8$; lower, $c/u_* = 11.5$. The dotted line corresponds to the height of the critical layer z_{cr} where $\langle u \rangle + u_w = 0$. Here $\langle u \rangle$ and u_w are the mean and phase averaged components of the horizontal velocity (see Sullivan *et al.*2000).**

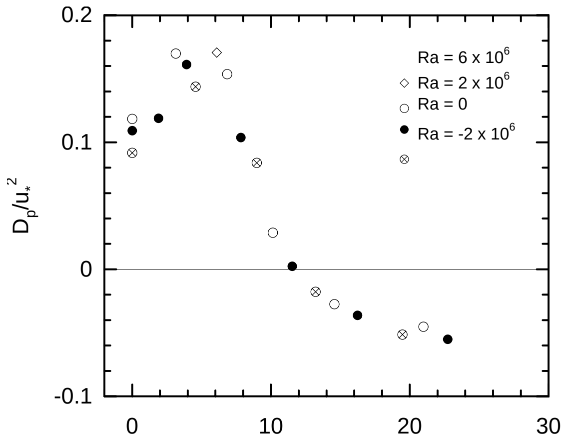

Figure 3: **Surface form stress, normalized by u_*^2, for several values of wave age c/u_* with varying Ra for unstable, neutral, and stable stratification (Sullivan & McWilliams 2000). The nondimensionalization is such that the stratification is unstable for $Ra > 0$ and stable for $Ra < 0$.**

boundary layer with stable interior stratification. McWilliams & Sullivan (2000b) generalized KPP for the regime of weakly convective Langmuir turbulence by modifying two of its rules: (1) an increasing value for the turbulent velocity scale, for decreasing Langmuir number La and (2) a decreasing value of the non-gradient flux coefficient. These modifications make the KPP turbulent flux profiles match reasonably well those in the LES case with Langmuir circulations present, especially so for material properties, and even more especially so for density and scalars with sources at the surface.

IMPACT/APPLICATIONS

These results confirm that turbulence resolving simulations can provide insight about the complex flow near the air-sea interface. The newly developed simulations codes that include a time dependent moving lower boundary provide flow details very near the air-water interface that are difficult to achieve with measurements and thus provide additional insight into air-sea coupling mechanisms.

TRANSITIONS & RELATED PROJECTS

These numerical results can potentially be used to help guide and interpret future low-wind CBLAST field campaigns, where stratification is expected to be important.

The Geophysical Turbulence Program at NCAR hosted a workshop for approximately 50 researchers and students on "Turbulence and the Air-Sea Interface" from 14-16 August, 2000. A link to the meeting abstracts can be found by browsing the web page at http://www.asp.ucar.edu/tasi.html#information.

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